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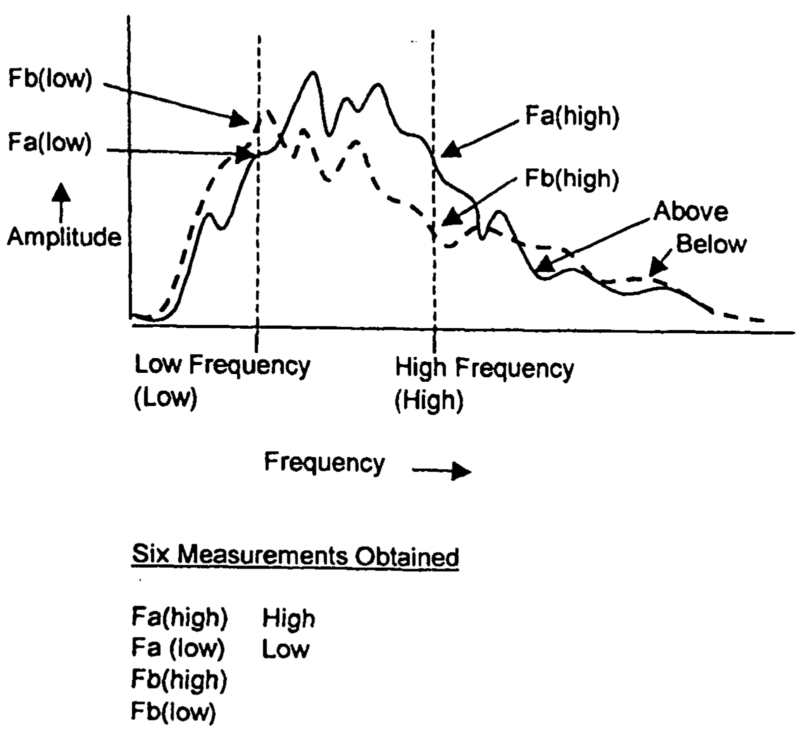
(54) Title: METHOD AND APPARATUS FOR DETECTING FRACTURES USING FREQUENCY DATA DERIVED FROM SEISMIC DATA



(57) Abstract: Geologic formations containing fractures are an important source of hydrocarbon accumulations and an interesting target for geophysical exploration. The presence of fractures in a geologic formation will act as a high-cut filter on the seismic wave propagation, producing a measurable change in the frequency spectra of the seismic signal above the fractured zone compared to the frequency of the signal below the zone. A unique method has been developed to show the presence of fractures in an Earth formation as a mappable attribute. This method uses the frequency spectra derived from P-wave seismic data over a pair of specific time windows above and below a seismic horizon or reflector of interest to infer the presence or absence of to these geologic fractures based on an attenuation of high frequencies. The method produces a parameter value (t*) that is proportional to the shift in frequency spectra amplitudes (i.e., energy) from higher frequencies to lower frequencies, that is, from a time-window above a horizon or reflector of interest to a time-window below the horizon or reflector of interest.

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METHOD AND APPARATUS FOR DETECTING FRACTURES USING FREQUENCY DATA DERIVED FROM SEISMIC DATA

The present invention relates to a method and apparatus responsive to a plurality of seismic data for generating a map illustrating data representative of a frequency shift of a plurality of seismic signals when said seismic signals propagate through a layer of fractured rock in an Earth formation.

Geologic formations containing fractures are an important source of hydrocarbon accumulations and an interesting target for geophysical exploration. The fractures in a geologic formation act as a high-cut filter with respect to a seismic wave that is propagating through the layer of fractured rock in the Earth formation. This filtering produces a measurable and mappable change in the frequency spectra of the seismic signal propagating above the fractured zone compared to the frequency spectra of the seismic signal propagating below the fractured zone.

Accordingly, in accordance with the present invention, a unique method has been developed to show the presence of fractures in an Earth formation as a mappable attribute. This method, described in detail below, uses the frequency spectra derived from P-wave seismic data, comprised of a plurality of seismic traces, over a pair of specific time windows, which are located above and below a seismic horizon or reflector of interest, to infer the presence or absence of these geologic fractures in a layer of fractured rock based on the preferential attenuation of high frequencies. The method produces a parameter (t^*), the parameter t^* being proportional to the shift in frequency spectra amplitudes (i.e., energy), from higher frequencies to lower frequencies, when the plurality of seismic traces propagate from the time-window located above the seismic horizon or reflector of interest, through the layer of fractured rock, to the time-window below the seismic horizon or reflector of interest. A map is generated based on the computation of t^* for all seismic traces in the seismic data.

Further scope of applicability of the present invention will become apparent from the detailed description presented herein. It should be understood, however, that

the detailed description and specific examples are given by way of illustration only, since various changes and modifications within the spirit and scope of the invention will be apparent to one skilled in the art from a reading of the following description and the accompanying drawings, which are given by way of illustration only and are not intended to be limitative of the present invention, and wherein:

Figure 1 illustrates a workstation with a CD-Rom adapted to be inserted therein for loading a workstation software package known as the 'Fracture Detection Software' in accordance with the present invention;

figure 2 illustrates a layer of fractured rock in an Earth formation;

figures 3 and 9 illustrate the layer of fractured rock including a first window above the fractured rock zone and another, second window below the fractured rock zone;

figure 4 illustrates the frequency spectrum of the seismic signal in the first window of figure 3;

figure 5 illustrates the frequency spectrum of the seismic signal in the second window of figure 3;

figures 6 and 10 illustrate the frequency spectra of figures 4 and 5 superimposed upon one another defining six measurement values;

figure 7 illustrates formula for defining 'F high', 'F low', and t*;

figures 8 and 11 illustrate a map of the fractured rock zone of figures 2 and 3, which maps the attribute t*;

figures 12 and 13A illustrate, graphically, how a frequency spectrum such as the frequency spectrum of figures 4 and/or 5 is generated using a Cosine Correlation Transform as embodied in the 'correlation transform software' disclosed herein in response to a seismic operation performed on a particular portion of an Earth formation;

figure 13B illustrates, in greater detail, how the 'correlation transform software' of figures 12 and 13A generates a frequency spectrum; and

figure 14 illustrates a flowchart of the 'correlation transform software' of figures 12, 13A, and 13B.

Referring first to figure 1, a workstation or other computer system 30 is illustrated. The computer system 30 may be, for example, a personal computer, a workstation, a mainframe, etc. Examples of possible workstations include a Silicon Graphics Indigo 2 workstation and a Sun SPARC workstation. The computer system 30 stores and executes a plurality of instructions that are used to detect fractures in an Earth formation in response to a plurality of seismic data 33, the seismic data 33 being provided as 'input data' to the computer system 30. The computer system 30 of figure 1 includes a processor 30a, a recorder to display device 30b, a memory 30c which is adapted to store the 'Fracture Detection Software' 30c1 in accordance with the present invention, and a system bus 30d to which the Processor 30a and the recorder or display device 30b and the memory 30c are connected. A CD-Rom 32 stores the 'Fracture Detection Software' 30c1 of the present invention, and, when the CD-Rom 32 is inserted into the computer system 30, the Fracture Detection Software 30c1 is loaded from the CD-Rom 32 into the memory 30c of the computer system 30. The processor 30a can now execute the 'Fracture Detection Software' 30c1 instructions and perform its fracture detection for detecting fractures in an Earth formation.

The process steps practiced by the 'Fracture Detection software' 30c1 of the present invention, when the instructions of the fracture detection software 30c1 are executed by the processor 30a of the computer system 30 of figure 1, are set forth below, followed by an explanation of each process step.

Process Steps

1. Interpret the reflector (horizon) on the seismic data, recording the two-way seismic travel time.

2. The interpreter specifies the length of the time window (e.g., 100 milliseconds) to extract the frequency spectra.

3. The same time window length is recommended, but not required, on the seismic trace above and below the reflector. This window will be relative to the travel time of the interpreted horizon (see step 1); that is, the window will be parallel to the geologic structure.

4. For every seismic trace where the horizon is interpreted, the interpreter generates two spectra; that is, a first spectrum located above the horizon, and a second spectrum located below the horizon. This operation can be performed using any number of transforms which result in a frequency representation of the data, i.e., Fast Fourier Transform, Wavelet Transform, Cosine Correlation, etc.

5. The interpreter extracts amplitudes for two specific frequencies (i.e., 10 Hz and 30 Hz) from the spectra above and below the horizon. The objective is to select a high and low frequency from the spectrum of each window (above and below the horizon) which are separated as far as possible in the usable bandwidth of the signal yet still contain valid amplitude (energy) above the background noise level. This can be generalized to any technique that measures the change in the energy (amplitude) distribution for the window above the horizon and the window below the horizon.

6. The amplitude values are used as inputs to the algorithm which computes the 't*' parameter for that seismic trace. Computation of t* is as follows:

$$F(high) = Fa(high) / Fb(high);$$

$$F(low) = Fa(low) / Fb(low)$$

$$t^* = \{ \ln[F(high)] - \ln [F(low)] \} / (high - low)$$

where:

F(high) is the ratio of the amplitudes for the higher frequency selected by the user (30 Hz for the example) taken from the window above, Fa(high), and the window below, Fb(high);

F(low) is the ratio of the amplitudes for the lower frequency selected by the user(10 hz for the example) taken from the window above, Fa(low), and the window below, Fb(low); and

t* is the computed attribute taken from the difference in the natural log (ln) of F(high) and F(low) and this difference then scaled (divided) by the difference in frequency between the measurement

points on the spectra (for the example: 30 Hz – 10 Hz = 20 Hz, 20 was used in the denominator of the t* formula).

7. These steps (1) – (6) are applied to every interpreted seismic trace.

8. The results (i.e., the t* parameter) are plotted on a map of the seismic survey. Areas of large t* values are more likely to contain a fractured formation. This map is generated using GEOFRAME® IESX® DK software, and GEOFRAME® BASEMAP software is used for visualizing a seismically derived attribute in a spatial context, both applications being provided by Schlumberger Technology Corporation (Houston, Texas).

Explanation of the Process Steps

Referring to figure 2, a layer of fractured rock in an Earth formation is illustrated. In figure 2, a layer of fractured rock 34 is located beneath the Earth's surface 36. Assume that an acoustic or explosive energy source 38 generates sonic vibrations or sound waves 40 and those sound waves 40 reflect off a horizon 42 in the Earth's formation. The reflected sound waves 40a are received by a geophone 44 and, as a result, a plurality of seismic traces are recorded in a recording truck 46.

Referring now to only 'one such seismic trace' among the plurality of seismic traces recorded in the recording truck 46, and specifically to figures 3 and 9, the 'one such seismic trace' 48 is illustrated in connection with the layer of fractured rock 34 in the formation of figure 2. In accordance with the novel method of the present invention, a window 50 is selected along the seismic trace 48 that is disposed above the fractured rock zone, and another window 52 is selected along the seismic trace 48 that is disposed below the fractured rock zone.

Referring to figure 4, a frequency spectrum of that portion of the seismic trace 48 that is disposed in the window 50 above the fractured rock zone 50 is generated. The frequency spectrum associated with that portion of the seismic trace 48 disposed inside the window 50 above the fractured rock zone 50 (hereinafter referred to as "Above") is illustrated in figure 4. The frequency spectrum "Above" of figure 4 can be generated by using the Fast Fourier Transform or a 'Cosine Correlation Transform'.

One example of the use of the Fast Fourier Transform is illustrated in U.S. Patent 5,870,691, Partyka, *et al.*, the disclosure of which is incorporated by reference into this specification. An example of the use of the 'Cosine Correlation Transform' is the method disclosed in U.S. Patent application Serial No. 10/017,565, filed 12/14/01, entitled "Seismic signal processing method and apparatus for generating correlation spectral volumes to determine geologic features", the disclosure of which is also incorporated by reference into this specification. The Cosine Correlation Transform disclosed in the referenced U.S. patent application is briefly described as follows, and with reference to figures 12, 13A, and 13B, in which a block diagram graphically illustrates how 'correlation transform software' performs a method for analyzing a set of seismic data.

As shown in figures 12 and 13A, each of a collection of synthetic time series (models or Kernel Functions) that represents a range of potential geologic features of interest is compared to a plurality of seismic traces on a narrow time window to identify which of the model traces best represents the seismic signature within that time window. Cross correlation is the preferred mathematical tool although many other methods would also work (e.g., differencing). An output volume is generated where the spatial location (geographic position) of the trace is the same as the input seismic trace, but whereas the third dimension on the seismic trace is two-way travel time, the third dimension of the Correlation Spectral Volume is the sequenced peak correlation values (in the case of cross-correlation) for the collection of synthetic model traces or Kernel Functions.

In figure 12, a 'system and corresponding analysis method for analyzing an input seismic volume to determine a set of geologic characteristics of an Earth Formation' is illustrated. Figure 12 shows initial 3D seismic data as an input. This technique generates the autocorrelation function within a user specified window such as the window 50, 52 above or below the fracture 34 and outputs these autocorrelation functions. Once the autocorrelation functions are generated, the autocorrelation functions are then cross correlated with a series of Kernel functions. In the embodiments disclosed herein, the Kernel functions do not include one or more traces

from an input seismic volume 146. Rather, the Kernel functions represent 'standard comparison traces having known geologic characteristics'. In particular, the Kernel functions are comprised of two or more traces having known geologic characteristics, whereas the autocorrelation functions are comprised of two or more traces having unknown geologic characteristics. One possible kernel function could be derived from the dominant spectral frequencies of a geologic section, such as 8, 37, and 65 hertz. In figure 12, the input seismic data, or volume 146 from the 'window of interest' either above or below fracture 34 (including a subset of the 'plurality of such seismic traces' 146) comprises a plurality of seismic traces in the 'window of interest'. Each of the seismic traces in the input seismic volume 146 undergoes autocorrelation (known as the 'autocorrelation technique') as described in U.S. Patent No. 6,151,555 to Van Bemmel, *et al.*, the disclosure of which is incorporated by reference into the specification of this application. As a result, a plurality of autocorrelation functions 150 are produced when the plurality of seismic traces in the input seismic data, or volume, 146 undergo autocorrelation via the 'autocorrelation technique'. A plurality of Kernel Functions 152 have already been generated. The Kernel Functions 152 are a collection of synthetic time series representing a range of potential geologic features of interest. That is, the Kernel Functions 152 include a plurality of 'seismic trace like' functions that inherently represent and correspond to a set of known geologic features of an Earth Formation. The Kernel Functions 152 correspond to the set of 'known' geologic features of the Earth Formation, since a set of all the 'known' geologic features inherent in each of the Kernel Functions 152 will be 'compared' (in a 'comparison technique') to a set of all the 'unknown' geologic features inherent in each of the autocorrelation functions 150. In accordance with one aspect of the present invention, that 'comparison technique' is a 'cross-correlation technique' as described in U.S. Patent No. 6,151,555, the disclosure of which has already been incorporated by reference into this specification. The 'cross-correlation technique' is also described in U.S. Patent No. 5,563,949 to Bahorich, *et al.*, the disclosure of which is also incorporated by reference into this specification. Thus, in figure 12, the 'Unknown geologic feature autocorrelation functions' 50 and the 'Known geologic

feature Kernel Functions' 52 are both provided as input data to the 'correlation transform software', which represents the correlation transform software in accordance with the present invention. Note that the correlation transform software generates an output 154 which is called a 'correlation spectral volume' 154.

The method for analyzing input seismic data/volume 146, discussed above with reference to figure 12, is set forth in more detail below with reference to figure 12 of the drawings. In figure 12, each of the Kernel Functions 152 undergoes cross-correlation with each of the Autocorrelation Functions 150, via the above-described correlation transform software, and as a result, the correlation spectral volume 154 is generated. To be more specific, Kernel Function (1) 152a is cross correlated with each of the Autocorrelation Functions 150 thereby generating row (1) 154a of the Correlation Spectral Volume 154. Then, Kernel Function (2) 152b is cross correlated with each of the Autocorrelation Functions 150 thereby generating row (2) 154b of the Correlation Spectral Volume 154. This process continues until the last remaining Kernel Function 152n is cross correlated with each of the Autocorrelation Functions 150, thereby generating the last remaining row of the Correlation Spectral Volume 154.

In figure 13A, a 'further system and corresponding analysis method for analyzing an input seismic volume to determine a set of geologic characteristics of an Earth Formation' is illustrated. Figure 13A shows an initial 3D seismic volume 146 as the input. This technique will generate a synthetic seismic wedge model at a user defined resolution using an existing seismic wavelet, or a wavelet extracted directly from the seismic data. Each trace of the synthetic seismic wedge model is then cross correlated with the seismic traces from a user defined zone of interest. The correlation functions are automatically picked and the resulting peak correlation values are stored in a 3D volume. In figure 13A, a geologic model 160 having known geologic characteristics is generated, and, from that geologic model 160, a synthetic model 162 consisting of a plurality of 'seismic trace like' traces and having the same 'Known' geologic characteristics is generated. In addition, the input seismic volume 146 which represents a 'window of interest' either above or below fracture 34 (including a subset

of the 'plurality of such seismic traces' 146) comprises a plurality of seismic traces in the 'window of interest'. As disclosed herein, the synthetic model 162 does not include one or more traces from the input seismic volume 146. Rather, the synthetic model 162 represents a set of 'standard comparison traces having known geologic characteristics'. In particular, the synthetic model 162 is comprised of two or more traces having known geologic characteristics, whereas the input seismic volume 146 of figure 13A is comprised of two or more traces having unknown geologic characteristics. The Correlation Transform Software receives the synthetic model 162 and the input seismic volume 146, and, responsive thereto, the Correlation Transform Software cross correlates each of the 'seismic trace like' traces of the Synthetic Model 162 with each of the traces in the 'window of interest' of the Input Seismic Volume 146 thereby generating a 'result' which comprises the Correlation Spectral Volume 154.

To be more specific, synthetic model 162 trace 162a is cross correlated, via the correlation transform software, with each of the traces 146a, 146b, ..., 146n of the input seismic volume 146 to thereby generate the first row 154a of correlation values on the Correlation Spectral Volume 154. That is, Synthetic Model 162 trace (1) 162a is cross correlated with each of the traces of the Input Seismic Volume 146, thereby generating row (1) 154a of the Correlation Spectral Volume 154. Then, Synthetic Model 162 trace (2) 162b is cross correlated with each of the traces of the Input Seismic Volume 146, thereby generating row (2) 154b of the Correlation Spectral Volume 154. This process continues until the last remaining Synthetic Model 162 trace (n) 162n is cross correlated with each of the traces of the Input Seismic Volume 146, thereby generating the last remaining row of the Correlation Spectral Volume 154.

In figure 13B, a more detailed discussion of the functional operation of the system and corresponding analysis method set forth in figures 12 and 13A, for analyzing an input seismic volume is illustrated. In figure 13B, the kernel functions or, alternatively, the synthetic model are represented by block 152/162; whereas the autocorrelation functions or, alternatively, the input seismic volume, are represented by

block 150/146. The correlation spectral volume is still represented by block 154 and the correlation transform software is still represented by block 114a. The kernel functions or synthetic model 152/162 include, by way of example only, traces 110, 112, 114, and 116. The autocorrelation functions or input seismic volume 150/146 includes, by way of example only, traces 120, 122, 124, 126, 128, and 130.

In operation, the first row of the correlation spectral volume 154 is plotted. Trace 110 of the Kernel functions or Synthetic model 152/162 is cross correlated, by using the correlation transform software 114a, with trace 120 of the autocorrelation functions or input seismic volume 150/146 to produce a value 'X1', which value 'X1' is plotted on the first row of the correlation spectral volume 154. Next, trace 110 is cross correlated with trace 122 to produce value 'X2' which is plotted on the first row of the correlation spectral volume 154. Next, trace 110 is cross correlated with trace 124 to produce value 'X3' which is plotted on the first row of the correlation spectral volume 154. Next, trace 110 is cross correlated with trace 126 to produce value 'X4' which is plotted on the first row of the correlation spectral volume 154. Next, trace 110 is cross correlated with trace 128 to produce value 'X5' which is plotted on the first row of the correlation spectral volume 154. Next, trace 110 is cross correlated with trace 130 to produce value 'X6' which is plotted on the first row of the correlation spectral volume 154. The first row of the correlation spectral volume 154 has now been completely plotted. Unique colors are assigned to the values 'X1' through 'X6' depending on the numerical values of 'X1' through 'X6'.

In figure 13B, the second row of the correlation spectral volume 154 is now plotted. Trace 112 of the kernel functions or synthetic model 152/162 is cross correlated, using the correlation transform software 114a, with trace 120 of the autocorrelation functions or input seismic volume 150/146 to produce value 'X7' which is plotted on the second row of the correlation spectral volume 154. Next, trace 112 is cross correlated with trace 122 to produce value 'X8' which is plotted on the second row of the correlation spectral volume 154. Next, trace 112 is cross correlated with trace 124 to produce value 'X9' which is plotted on the second row of the correlation spectral volume 154. Next, trace 112 is cross correlated with trace 126 to

produce value 'X10' which is plotted on the second row of the correlation spectral volume 154. Next, trace 112 is cross correlated with trace 128 to produce value 'X11' which is plotted on the second row of the correlation spectral volume 154. Next, trace 112 is cross correlated with trace 130 to produce value 'X12' which is plotted on the second row of the correlation spectral volume 154. Unique colors are assigned to the values 'X7' through 'X12' depending on the numerical values of 'X7' through 'X12'.

Next, the third row of the correlation spectral volume 154 is plotted. Trace 114 of the Kernel functions or Synthetic model 152/162 is cross correlated, using the correlation transform software 114a, with trace 120 of the autocorrelation functions or input seismic volume 150/146 to produce value 'X13' which is plotted on the third row of the correlation spectral volume 154. Trace 114 is then cross correlated with trace 122 to produce value 'X14' which is plotted on the third row of the correlation spectral volume 154. Next, trace 114 is cross correlated with trace 124 to produce value 'X15' which is plotted on the third row of the correlation spectral volume 154. Next, trace 114 is cross correlated with trace 126 to produce value 'X16' which is plotted on the third row of the correlation spectral volume 154. Next, trace 114 is cross correlated with trace 128 to produce value 'X17' which is plotted on the third row of the correlation spectral volume 154. Next, trace 114 is cross correlated with trace 130 to produce value 'X18' which is plotted on the third row of the correlation spectral volume 154. Unique colors are assigned to the values 'X13' through 'X18' depending on the numerical values of 'X13' through 'X18'.

The fourth row of the correlation spectral volume 154 is then plotted.. Trace 116 of the Kernel functions or Synthetic model 152/162 is cross correlated, using the correlation transform software 114a, with trace 120 of the autocorrelation functions or input seismic volume 150/146 to produce value 'X19' which is plotted on the fourth row of the correlation spectral volume 154. Next, trace 116 is cross correlated with trace 122 to produce value 'X20' which is plotted on the fourth row of the correlation spectral volume 154. Next, trace 116 is cross correlated with trace 124 to produce value 'X21' which is plotted on the fourth row of the correlation spectral volume 154.

Next, trace 116 is cross correlated with trace 126 to produce value 'X22' which is plotted on the fourth row of the correlation spectral volume 154. Next, trace 116 is cross correlated with trace 128 to produce value 'X23' which is plotted on the fourth row of the correlation spectral volume 154. Next, trace 116 is cross correlated with trace 130 to produce value 'X24' which is plotted on the fourth row of the correlation spectral volume 154. Unique colors are assigned to the values 'X19' through 'X24' depending on the numerical values of 'X19' through 'X24'.

Referring to figure 14, a detailed flowchart of the Correlation Transform Software 14a of figures 12, 13A, and 13B is illustrated. Beginning at the 'start' position 70, in a decision triangle 72, a decision must be made whether to use the 'synthetic model option' 74 illustrated in figure 13 or the 'kernel function option' 76 illustrated in figure 12. Using the 'kernel function option' 76 first, the next step is to execute the 'Compute Autocorrelations and Generate Kernel Suite' block 78. This block 78 receives 3D Seismic data 146 (representing the 'Input Seismic Volume' 46 in figure 12) from the 'Input 3D Seismic Data' block 80 in figure 14. This block 78 generates three outputs: full trace autocorrelations 82 and window autocorrelations 84 representing Autocorrelation Functions 150 in figure 12, and Kernel Functions 86 representing Kernel Functions 152 in figure 12. Recall that the Autocorrelation Functions 150 in figure 12 include only a portion of the full trace autocorrelations that are included within a certain window. In response to the full trace autocorrelation/window autocorrelation 82, 84 and the kernel functions 86, block 88 of figure 14 entitled 'Generate Correlation Spectral Volume' will now generate the Correlation Spectral Volume 154 of figure 12 in the manner discussed above with reference to figure 12. The Correlation Spectral Volume 154 of figure 12, output from block 88 in figure 14, is provided as an output in the 'Output 3D CSV' block 90. Alternatively, the Correlation Spectral Volume 154 of figure 12 output from block 88 in figure 14, undergoes normalization via the 'Normalize Spectral Volume' block 92; in this case, the 'normalized Correlation Spectral Volume' is provided as an output in the 'Output 3D CSV Normalized' block 94.

A frequency spectrum of that portion of the seismic trace 48 that is disposed in the window 52 below the fractured rock zone 52 is also generated. The frequency spectrum associated with that portion of the seismic trace 48 which is disposed inside the window 52 below the fractured rock zone 52 (hereinafter referred to as "Below") is illustrated in figure 5. The frequency spectrum "Below" of figure 5 can be generated by using the Fast Fourier Transform or a 'Cosine Correlation Transform'. One example of the use of the Fast Fourier Transform is illustrated in the above-incorporated U.S. Patent 5,870,691, Partyka *et al.* An example of the use of the 'Cosine Correlation Transform' is disclosed in the above-incorporated U.S. Patent application Serial No. 10/017,565, entitled "Seismic signal processing method and apparatus for generating correlation spectral volumes to determine geologic features."

Referring to figures 6 and 10, a frequency spectrum is illustrated, where the frequency spectra of figure 4 (i.e, 'Above') is superimposed over the frequency spectra of figure 5 (i.e., 'Below'). In the frequency spectrum of figure 6, low frequency 'Low' and a high frequency 'High' are selected along the 'x' frequency axis. Using the 'Low' frequency in figure 6, an amplitude is located on the 'y' amplitude axis of the 'Above' frequency spectra, 'Fa(low)', and an amplitude is located on the 'y' amplitude axis of the 'Below' frequency spectra, 'Fb(low)'. Using the 'High' frequency in figure 6, an amplitude is located on the 'y' amplitude axis of the 'Above' frequency spectra, 'Fa(high)', and an amplitude is located on the 'y' amplitude axis of the 'Below' frequency spectra, 'Fb(high)'. As noted in figure 6, six different values or measurements have now been defined as follows: (1) Low, (2) High, (3) Fa(low), (4) Fb(low), (5) Fa(high), and (6) Fb(high). Each of these six values or measurements is used in an algorithm to be described below with reference to figure 7.

Referring to figure 7, define the value 'F high' as follows:

$$F\ high = Fa(high)/Fb(high)$$

Define a value 'F low' as follows:

$$F\ low = Fa(low)/Fb(low)$$

From the values 'F high' and 'F low', define an attribute, hereinafter called the "t* attribute", as follows:

$$t^* = [\ln(F\ high) - \ln(F\ low)]/(High - Low)$$

Referring back to figure 3, the t* attribute can be defined as follows: recalling that the seismic trace 48 has a particular frequency before the trace 48 propagates through the layer of fractured rock 34, the t* attribute represents an indication of how much that frequency (of the seismic trace 48) shifts or changes when the seismic trace 48 propagates through the layer of fractured rock 34 in figure 3.

Referring to figure 8, recalling that the seismic trace 48 of figure 3 intersected the horizon 42 at a location on the horizon defined by the (x, y) coordinates (x1, y1), a 'map of the fractured zone' can be plotted. On the 'map', the above defined 't*' attribute is plotted at the same coordinate location (x1, y1). Recall that the seismic trace 48 intersected the horizon 42 at coordinate location (x1, y1). Then, a unique color is assigned to the 't*' attribute which is plotted on the map, the unique color corresponding directly to the t* attribute value plotted on the map. For each t* attribute value plotted on the map, a corresponding and possibly different and unique color is assigned to each t* attribute. As a result, a user can see the color on the map and associate the color on the map to a unique t* attribute value.

Referring to figure 11, the above process plotted the t* attribute on the 'map' using a single seismic trace 48. When the process is repeated for all other seismic traces recorded by the geophone 44 that are representative of the reflected sound vibrations 40a of figure 2, the "map of the Fractured Zone" of figure 11 is the result.

The invention being thus described, it will be obvious that the same may be varied in many ways. Such variations are not to be regarded as a departure from the spirit and scope of the invention, and all such modifications as would be obvious to one skilled in the art are intended to be included within the scope of the following claims.

WHAT IS CLAIMED IS:

1. A method of detecting fractures in a fractured zone in an Earth formation, a plurality of acoustic waves propagating through the fractured zone and reflecting off a horizon in the formation and, responsive thereto, a plurality of seismic traces representative of said acoustic waves propagating through said fractured zone being received and recorded, a first portion of said seismic traces corresponding to a first window located above said fractured zone in said formation, and a second portion of said seismic traces corresponding to a second window located below said fractured zone in said formation, said method comprising the steps of:

generating a first frequency spectrum associated with said first portion of said seismic traces corresponding to said first window;

generating a second frequency spectrum associated with said second portion of said seismic traces corresponding to said second window;

superimposing said first frequency spectrum onto said second frequency spectrum thereby generating a superimposed frequency spectrum and defining from the superimposed frequency spectrum a low frequency (low) and a high frequency (high);

when said low frequency and said high frequency is defined, further defining from the superimposed frequency spectrum a plurality of amplitude values, said plurality of amplitude values including: Fa(high), Fa(low), Fb(high), and Fb(low);

from said plurality of amplitude values, defining a t* attribute; and

plotting the t* attribute value on a map and assigning a unique color to said t* attribute value.

2. The method of claim 1 wherein the step of defining a t* attribute value from said plurality of amplitude values comprises the step of defining a value 'F high' from a first formula, as follows:

$$F\ high = Fa(high)/Fb(high).$$

3. The method of claim 2 wherein the step of defining a t* attribute value from said plurality of amplitude values further comprises the step of defining a value 'F low' from a second formula, as follows:

$$F\ low = Fa(low)/Fb(low).$$

4. The method of claim 3 wherein the step of defining a t* attribute value from said plurality of amplitude values further comprises the step of defining said t* attribute value from a third formula, as follows:

$$t^* = [\ln (F\ high) - \ln (F\ low)]/(High - Low).$$

5. A program storage device readable by a machine, tangibly embodying a program of instructions executable by the machine to perform method steps for detecting fractures in a fractured zone in an Earth formation, a plurality of acoustic waves propagating through the fractured zone and reflecting off a horizon in the formation and, responsive thereto, a plurality of seismic traces representative of said acoustic waves propagating through said fractured zone being received and recorded, a first portion of said seismic traces corresponding to a first window located above said fractured zone in said formation, and a second portion of said seismic traces corresponding to a second window located below said fractured zone in said formation, said method steps comprising:

generating a first frequency spectrum associated with said first portion of said seismic traces corresponding to said first window;

generating a second frequency spectrum associated with said second portion of said seismic traces corresponding to said second window;

superimposing said first frequency spectrum onto said second frequency spectrum thereby generating a superimposed frequency spectrum and defining from the superimposed frequency spectrum a low frequency (low) and a high frequency (high);

when said low frequency and said high frequency is defined, further defining from the superimposed frequency spectrum a plurality of amplitude values, said plurality of amplitude values including: Fa(high), Fa(low), Fb(high), and Fb(low);

from said plurality of amplitude values, defining a t* attribute; and

plotting the t* attribute value on a map and assigning a unique color to said t* attribute value.

6. The program storage device of claim 5 wherein the step of defining a t* attribute value from said plurality of amplitude values comprises the step of defining a value 'F high' from a first formula, as follows:

F high = Fa(high)/Fb(high).

7. The program storage device of claim 6 wherein the step of defining a t* attribute value from said plurality of amplitude values further comprises the step of defining a value 'F low' from a second formula, as follows:

F low = Fa(low)/Fb(low).

8. The program storage device of claim 7 wherein the step of defining a t* attribute value from said plurality of amplitude values further comprises the step of: defining said t* attribute value from a third formula, as follows:

t* = [ln (F high) – ln (F low)]/(High – Low).

9. An apparatus adapted for detecting fractures in a fractured zone in an Earth formation, a plurality of acoustic waves propagating through the fractured zone and reflecting off a horizon in the formation and, responsive thereto, a plurality of seismic traces representative of said acoustic waves propagating through said fractured zone being received and recorded, a first portion of said seismic traces corresponding to a first window located above said fractured zone in said formation, and a second portion of said seismic traces corresponding to a second window located below said fractured zone in said formation, said apparatus comprising:

first means for generating a first frequency spectrum associated with said first portion of said seismic traces corresponding to said first window;

second means for generating a second frequency spectrum associated with said second portion of said seismic traces corresponding to said second window;

third means for superimposing said first frequency spectrum onto said second frequency spectrum thereby generating a superimposed frequency

spectrum and defining from the superimposed frequency spectrum a low frequency (low) and a high frequency (high);

fourth means for further defining, from the superimposed frequency spectrum, a plurality of amplitude values when said low frequency and said high frequency is defined, said plurality of amplitude values including: Fa(high), Fa(low), Fb(high), and Fb(low);

fifth means for defining a t* attribute from said plurality of amplitude values; and

sixth means for plotting the t* attribute value on a map and assigning a unique color to said t* attribute value.

10. The apparatus of claim 9 wherein said fifth means for defining a t* attribute value from said plurality of amplitude values comprises means for defining a value 'F high' from a first formula, as follows:

$$F\ high = Fa(high)/Fb(high).$$

11. The apparatus of claim 10 wherein said fifth means for defining a t* attribute value from said plurality of amplitude values further comprises means for defining a value 'F low' from a second formula, as follows:

$$F\ low = Fa(low)/Fb(low).$$

12. The apparatus of claim 11 wherein said fifth means for defining a t* attribute value from said plurality of amplitude values further comprises means for defining said t* attribute value from a third formula, as follows:

$$t^* = [\ln (F\ high) - \ln (F\ low)]/(High - Low).$$

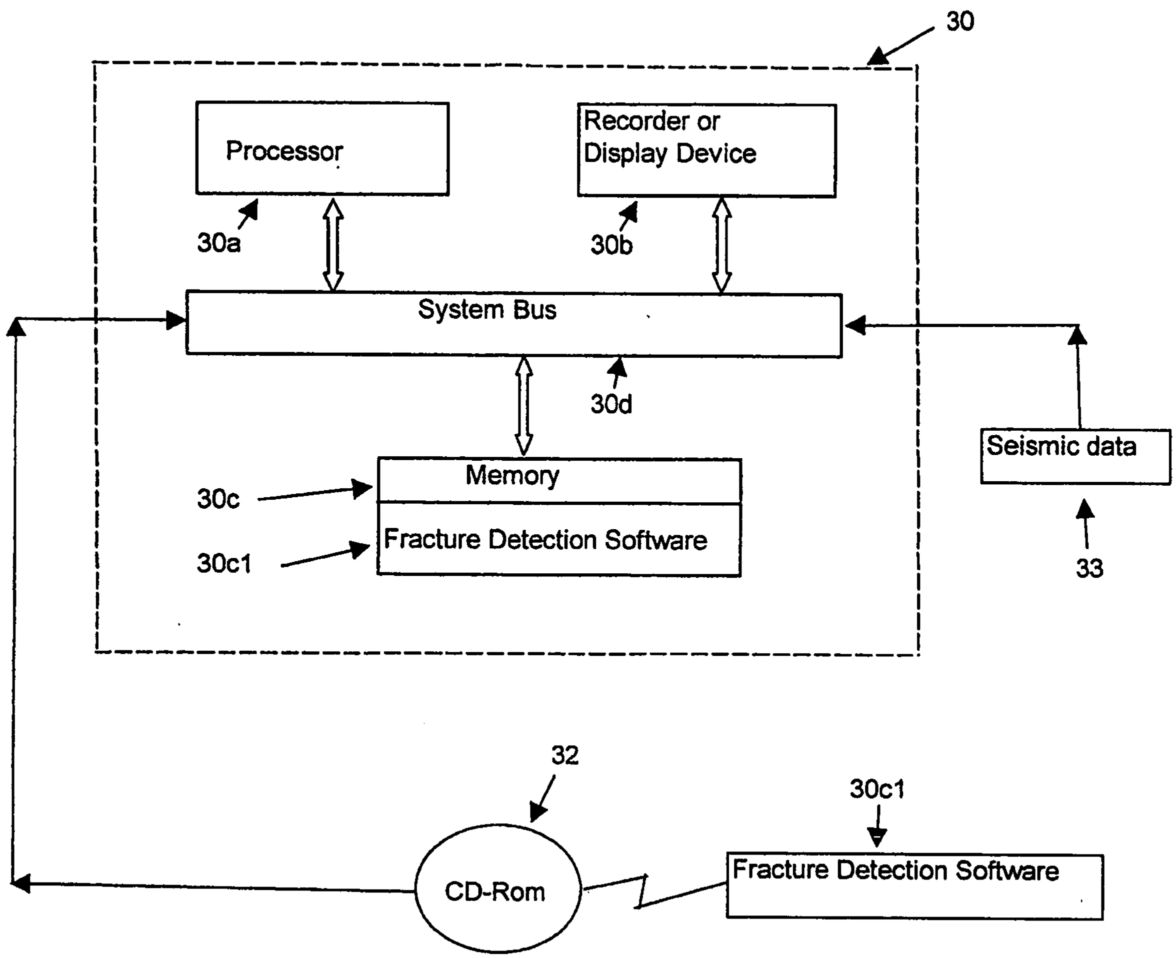

30
Processor
Recorder or
Display Device
30a
30b
System Bus
30d
Seismic data
Memory
30c
Fracture Detection Software
30c1
33
32
30c1
CD-Rom
Fracture Detection Software

FIG 1

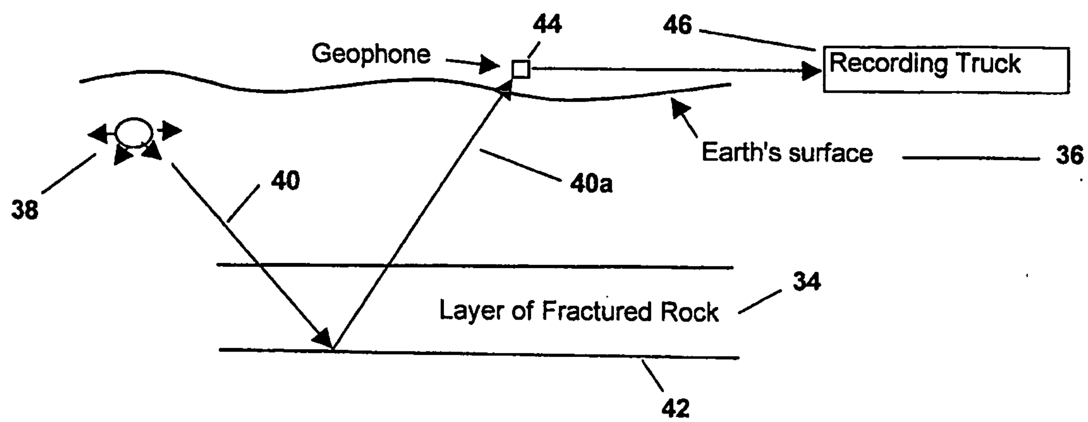


FIG 2

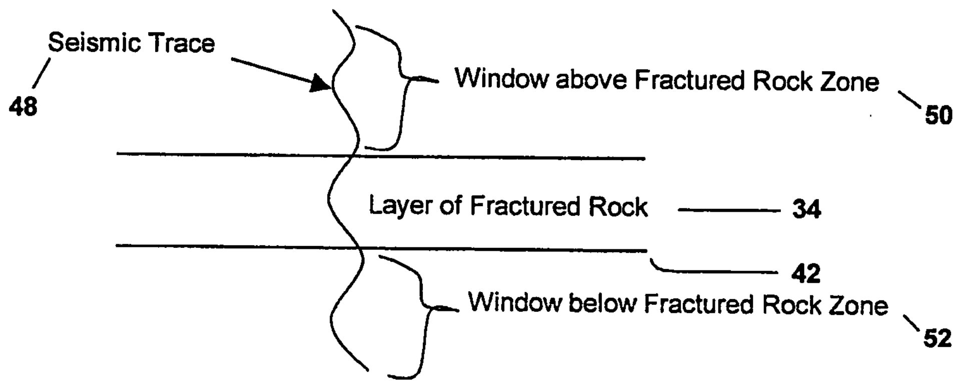


FIG 3

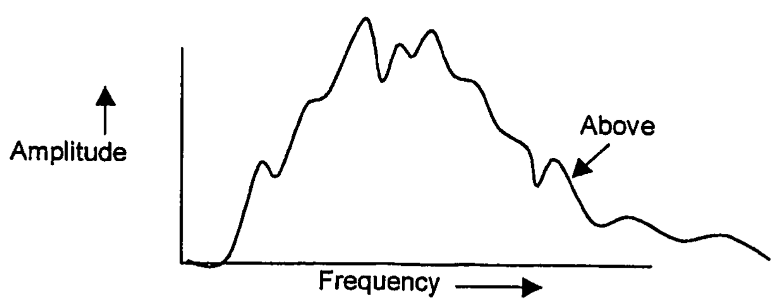


FIG 4

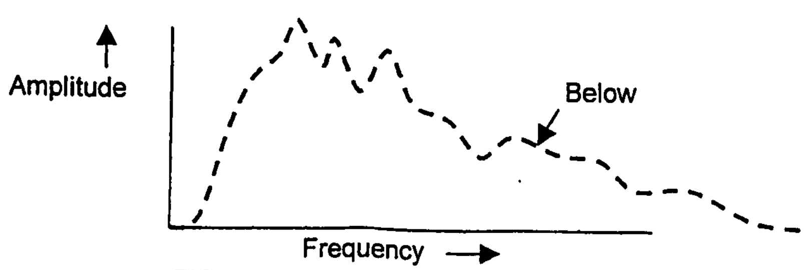
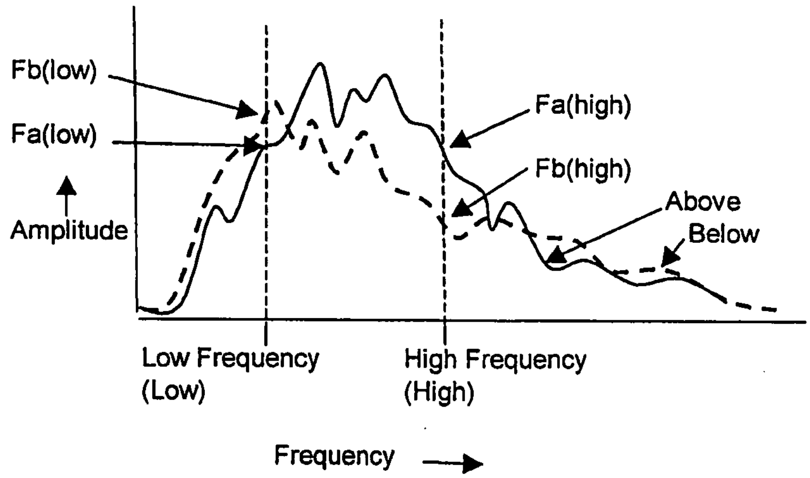


FIG 5



<u>Six Measurements Obtained</u>

Fa(high)	High
Fa (low)	Low
Fb(high)	
Fb(low)	

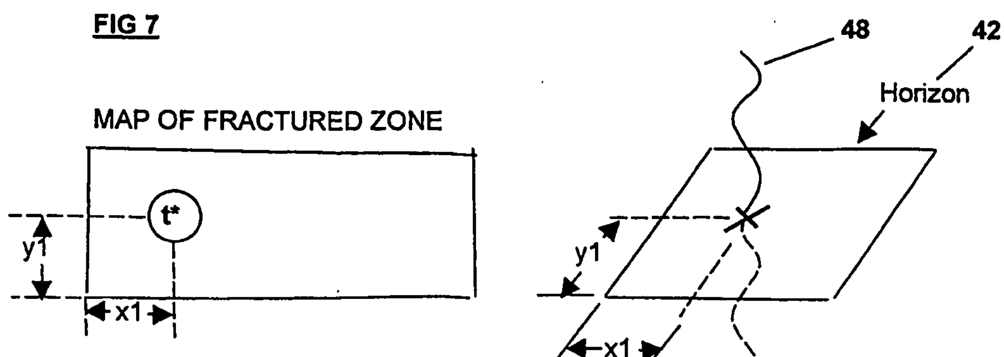
<u>FIG 6</u>

F high = Fa(high)/Fb(high)

F low = Fa(low)/Fb(low)

t* = [ln (F high) - ln (F low)]/(High - Low)

<u>FIG 7</u>



<u>FIG 8</u>

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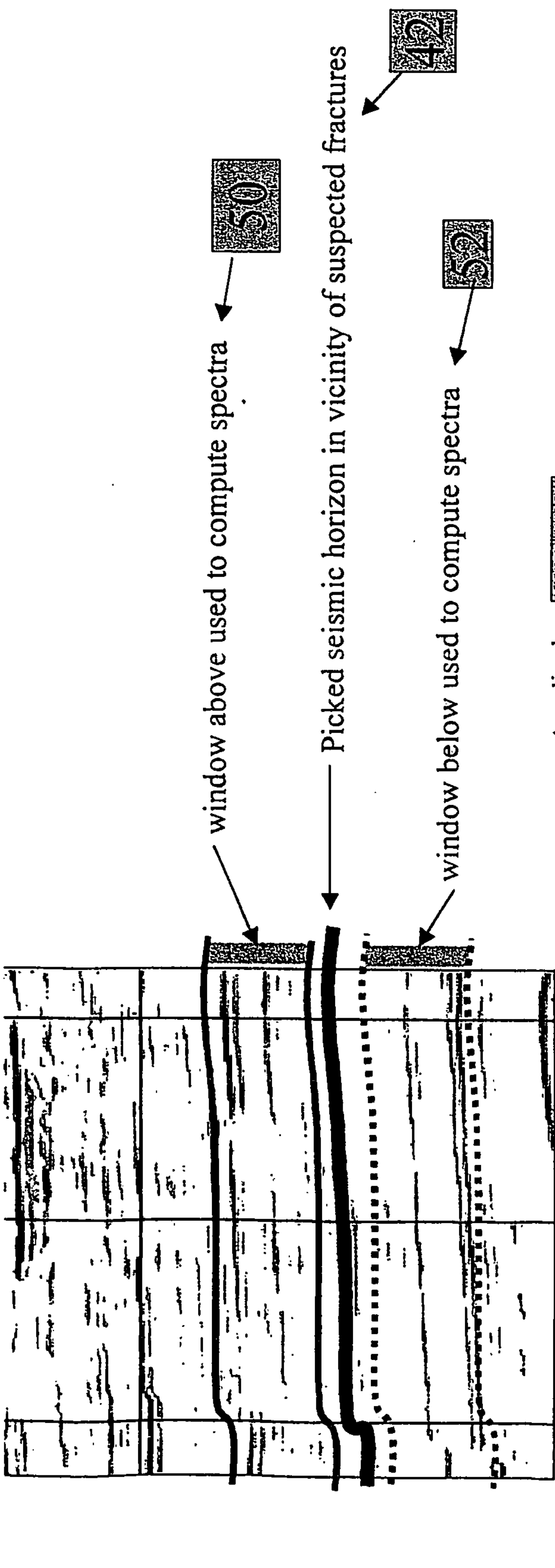
50
window above used to compute spectra
42
Picked seismic horizon in vicinity of suspected fractures
52
window below used to compute spectra

FIG 9

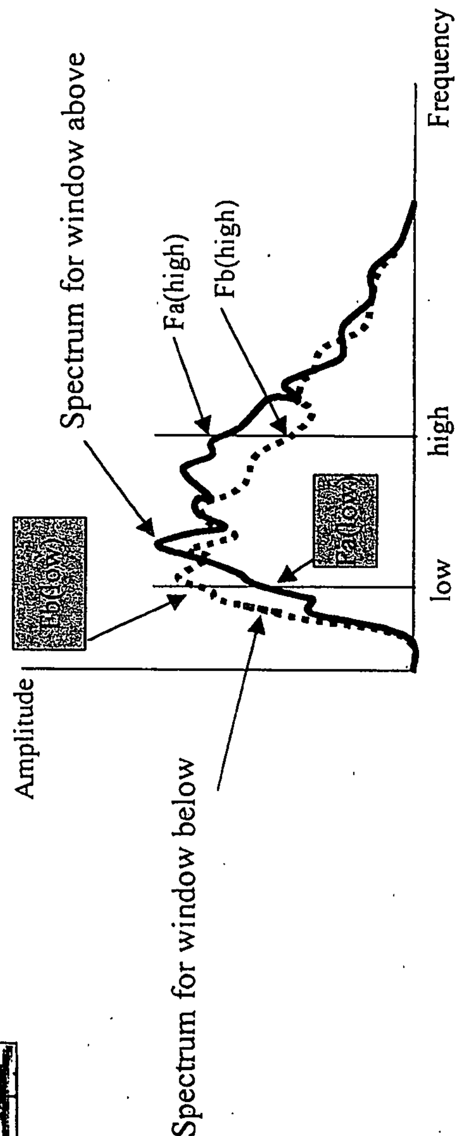
Spectrum for window above
Fa(high)
Fb(high)
Fb(low)
Fa(low)
Amplitude
low
high
Frequency
Spectrum for window below

FIG 10

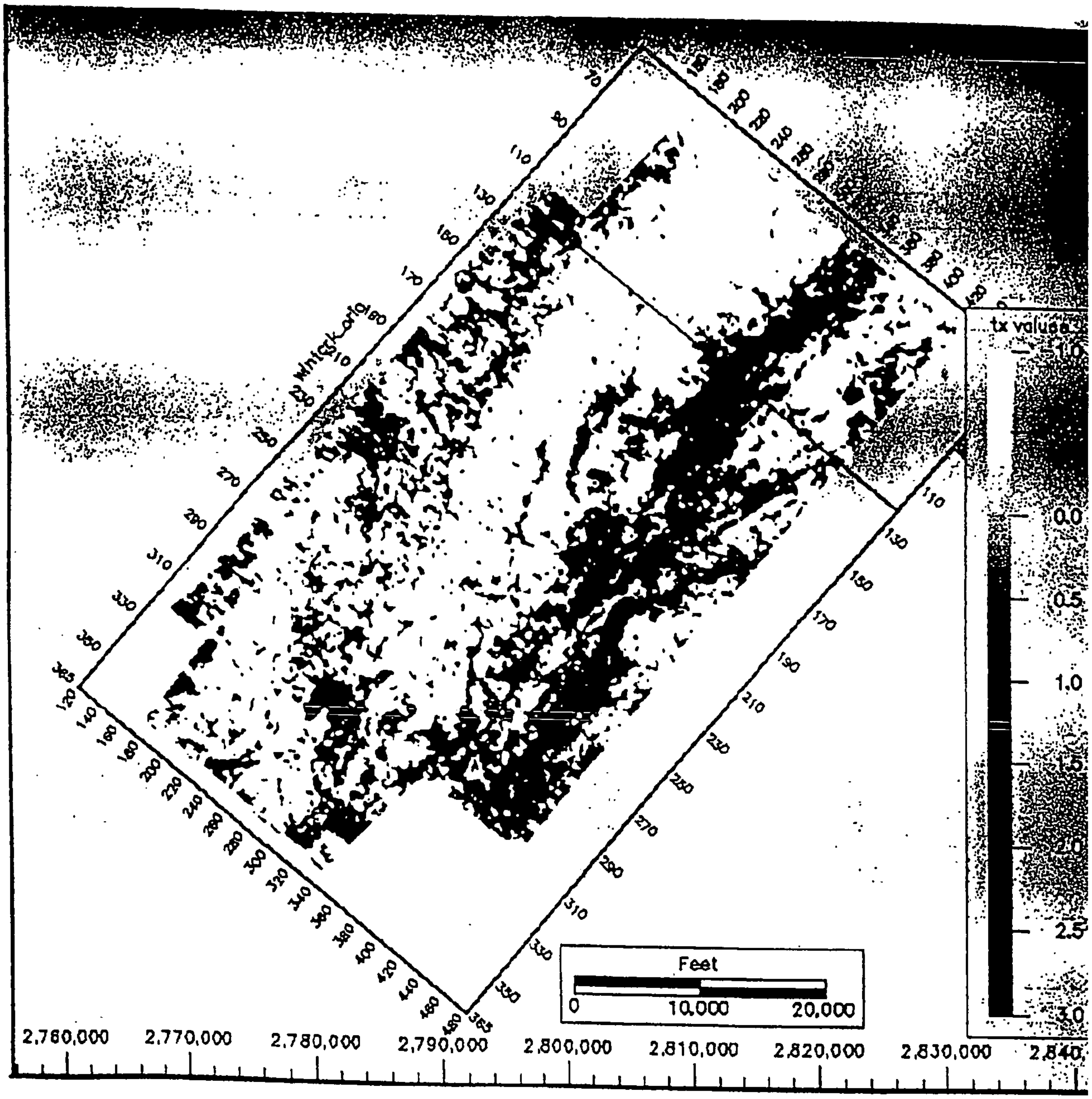

Fig 11

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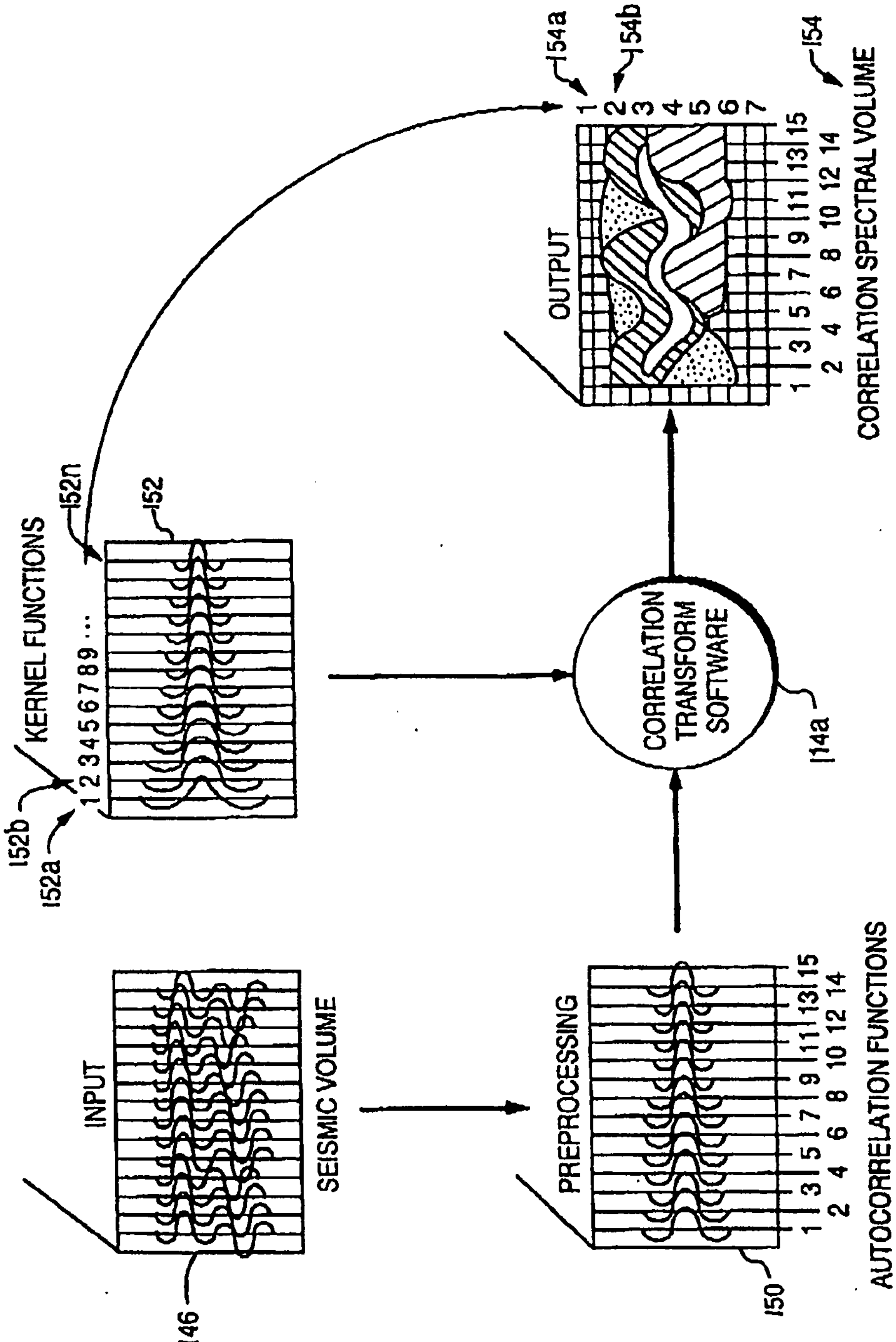
INPUT
SEISMIC VOLUME
146
PREPROCESSING
AUTOCORRELATION FUNCTIONS
150
KERNEL FUNCTIONS
1 2 3 4 5 6 7 8 9 ...
152
152a
152b
152n
CORRELATION TRANSFORM SOFTWARE
114a
OUTPUT
CORRELATION SPECTRAL VOLUME
154
154a
154b

FIG. 12

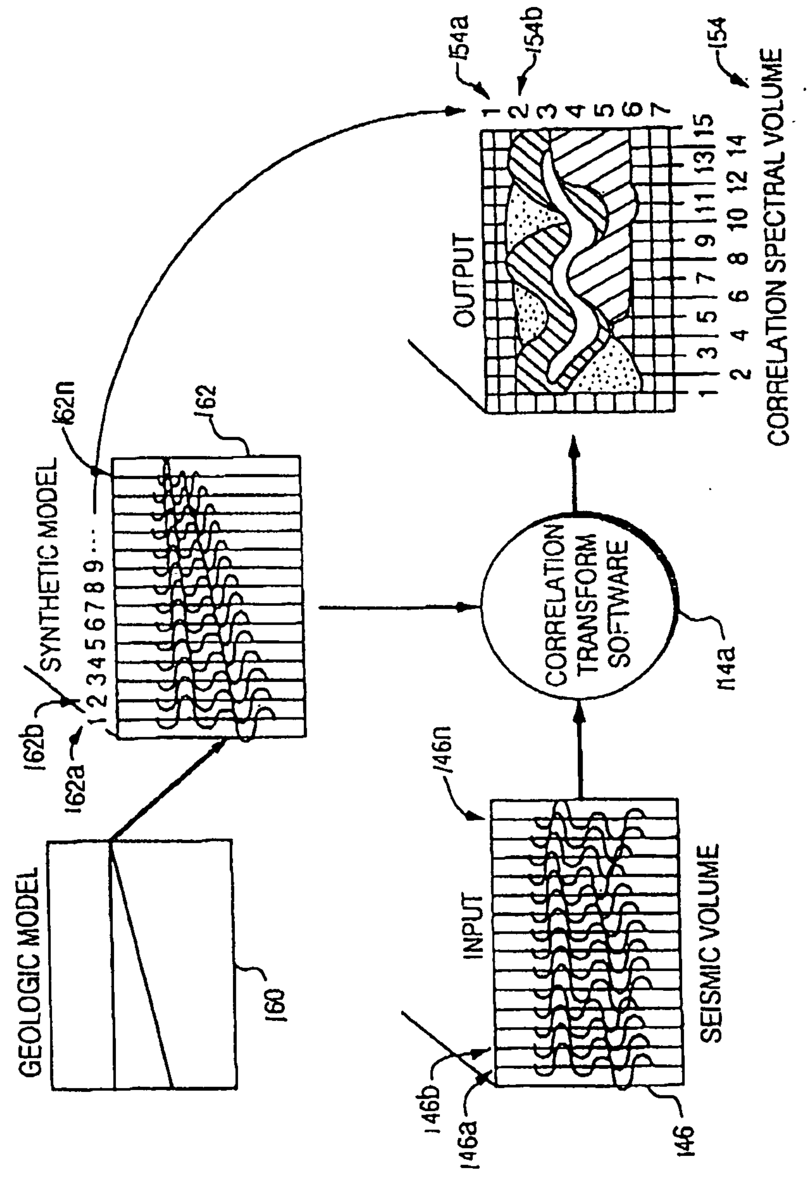
GEOLOGIC MODEL
160
SYNTHETIC MODEL
1 2 3 4 5 6 7 8 9 ...
162a
162b
162n
162
INPUT
SEISMIC VOLUME
146a
146b
146n
146
CORRELATION TRANSFORM SOFTWARE
114a
OUTPUT
CORRELATION SPECTRAL VOLUME
154a
154b
154
1 2 3 4 5 6 7
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15

FIG. 13A

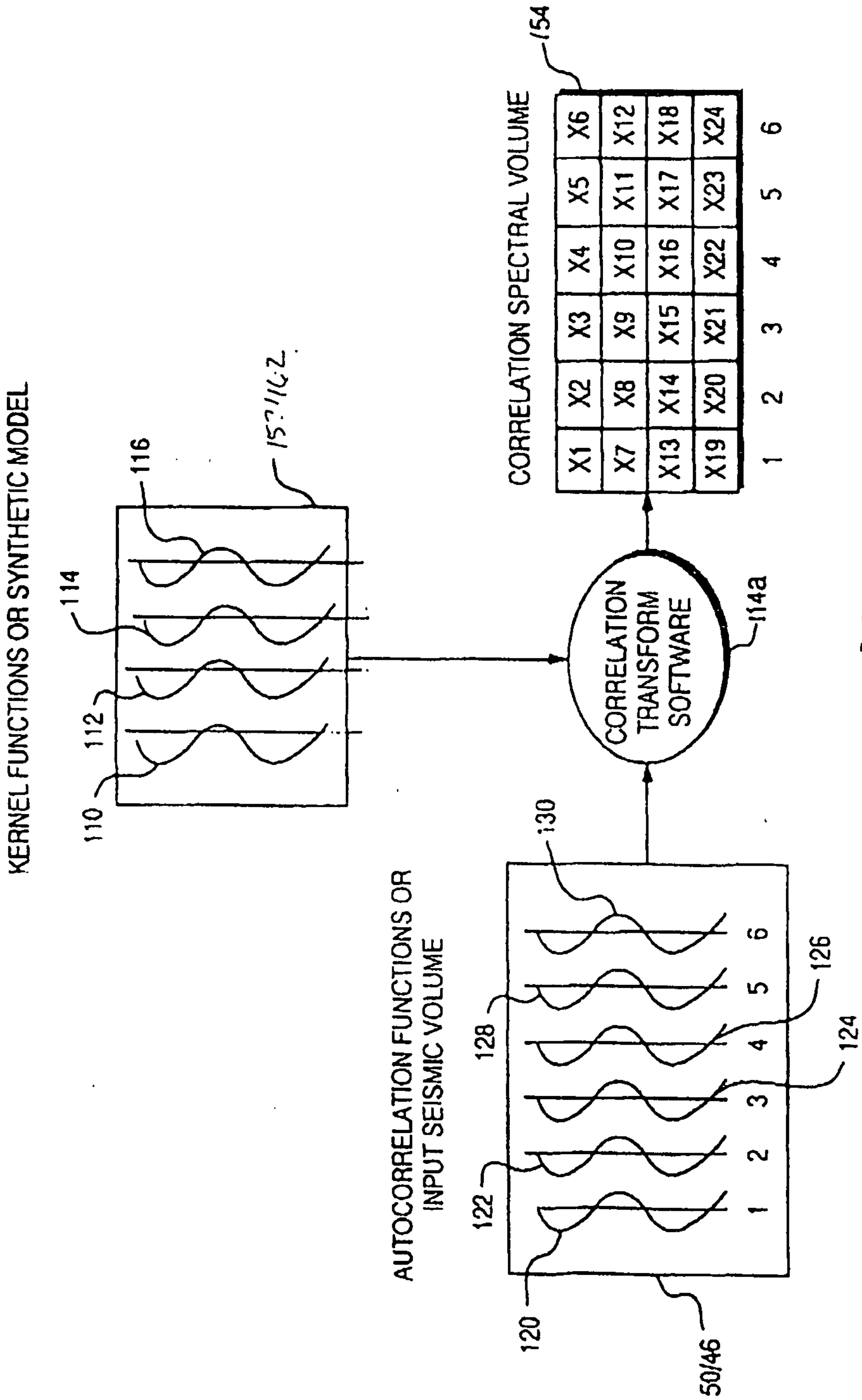
KERNEL FUNCTIONS OR SYNTHETIC MODEL
110
112
114
116
CORRELATION TRANSFORM SOFTWARE
114a
CORRELATION SPECTRAL VOLUME
154
X1 X2 X3 X4 X5 X6
X7 X8 X9 X10 X11 X12
X13 X14 X15 X16 X17 X18
X19 X20 X21 X22 X23 X24
1 2 3 4 5 6
AUTOCORRELATION FUNCTIONS OR INPUT SEISMIC VOLUME
120
122
124
126
128
130
1 2 3 4 5 6
50/46

FIG. 13B

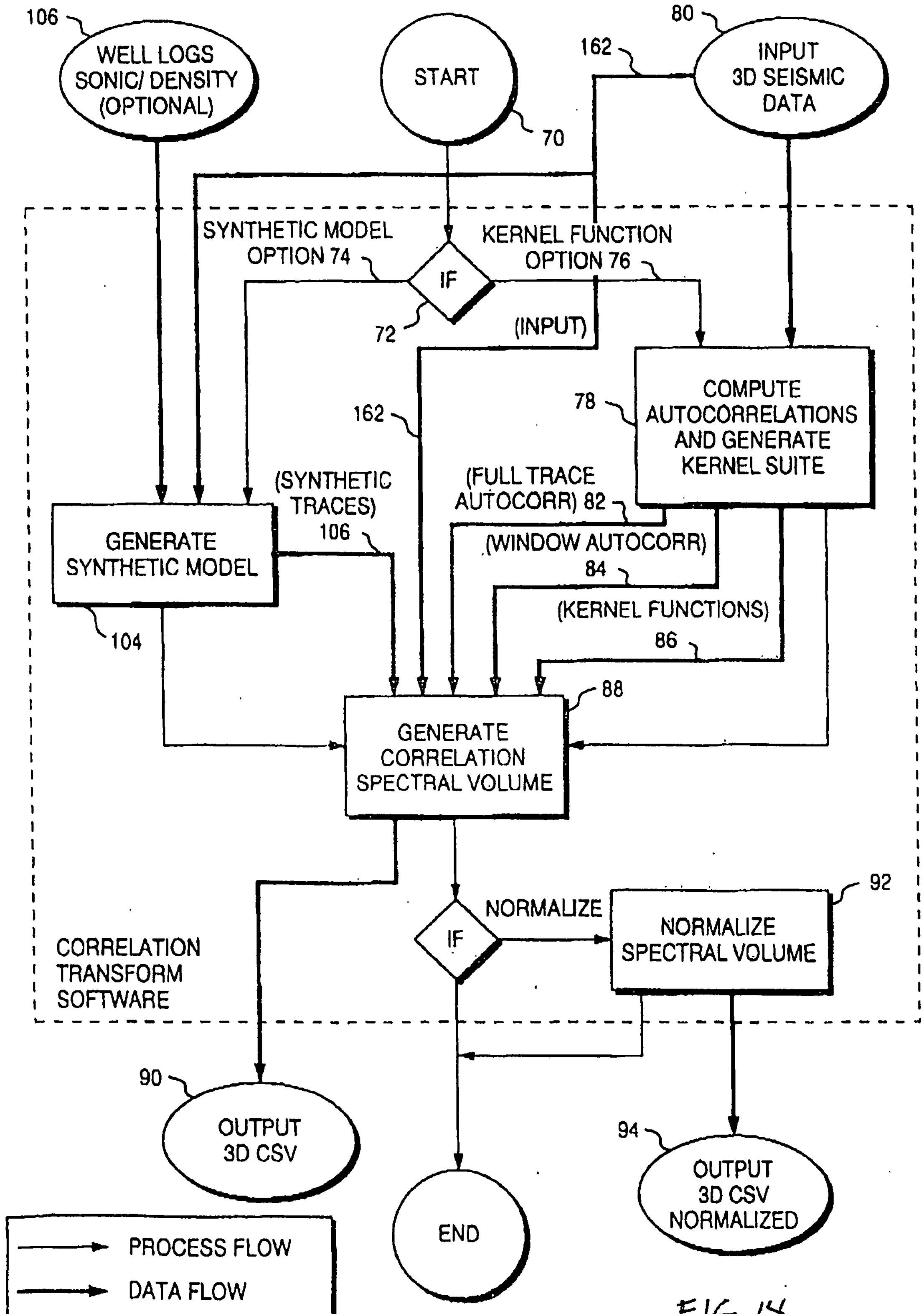
106
WELL LOGS SONIC/ DENSITY (OPTIONAL)
START
70
80
INPUT 3D SEISMIC DATA
162
SYNTHETIC MODEL OPTION 74
IF
72
KERNEL FUNCTION OPTION 76
(INPUT)
162
78
COMPUTE AUTOCORRELATIONS AND GENERATE KERNEL SUITE
(SYNTHETIC TRACES) 106
GENERATE SYNTHETIC MODEL
104
(FULL TRACE AUTOCORR) 82
(WINDOW AUTOCORR) 84
(KERNEL FUNCTIONS) 86
88
GENERATE CORRELATION SPECTRAL VOLUME
IF
NORMALIZE
NORMALIZE SPECTRAL VOLUME
92
CORRELATION TRANSFORM SOFTWARE
90
OUTPUT 3D CSV
END
94
OUTPUT 3D CSV NORMALIZED
PROCESS FLOW
DATA FLOW

FIG. 14